Si Detectors in Nuclear and High Energy Physics Experiments and BNL's Detector Development and Processing Capabilities

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OUTLINE

- **Detector material and configurations**

- **Various Si detectors**
  - **Existing technologies (good for sPHENIX, 5 years)**
  - **New technologies (good for ePHENIX, 10 years)**
- **Detector processing facilities**
  - **National labs and universities**
  - **Commercial**
  - **BNL detector development and processing capabilities**
- **Summary**

Semiconductor Materials For Particle Detectors

	Density (g/cm^3)	Bandgap (eV)	Dielectric constant	Displace-ment threshold energy (eV)	e-h creation energy (eV)	μ_e (cm/s/V)	μ_h (cm/s/V)	# of e-h pairs/0.3% X_0
Si	2.3	1.12	11.9	13.5	3.6	1450 Good e mobility	450 Good h mobility	24k Good signal
C (Diamond)	3.5	5.5 Very low leakage current at RT	5.7 Small capacitance	80 Much less lattice damage	13-17	1800 Good e mobility	1200 Very good h mobility	7.2k Low signal
SiC	3.2	3.3 Low leakage current at RT	9.7	30 Less lattice damage	9	400-900 Modest e mobility	20-50 Poor h mobility	13k
Ge	5.3 Hi Z, good for hard X-ray	0.66 Hi leakage current at RT	16 Large capacitance	15	3	3900 Very good e mobility	1900 Very good h mobility	16k
CdTe	5.9 Hi Z, good for hard X-ray	1.49	10	6.7	5	1050 Good e mobility	100 Poor h mobility	6.6k Low signal

Why do we concentrate our efforts on Si detectors?

Si is by far the most used material for particle detectors for its:

- **Abundance on earth**
- **Mature and reproducible wafer manufacture**
- **Natural oxide for passivation and masking**
- **Mature processing technology (easy for segmentation, small segmentations and integration)**
- **Radiation hardness**
- **Used extensively and successfully in experiments**
- **Choices: use something exist and working (less cost) or something new requires R&D**

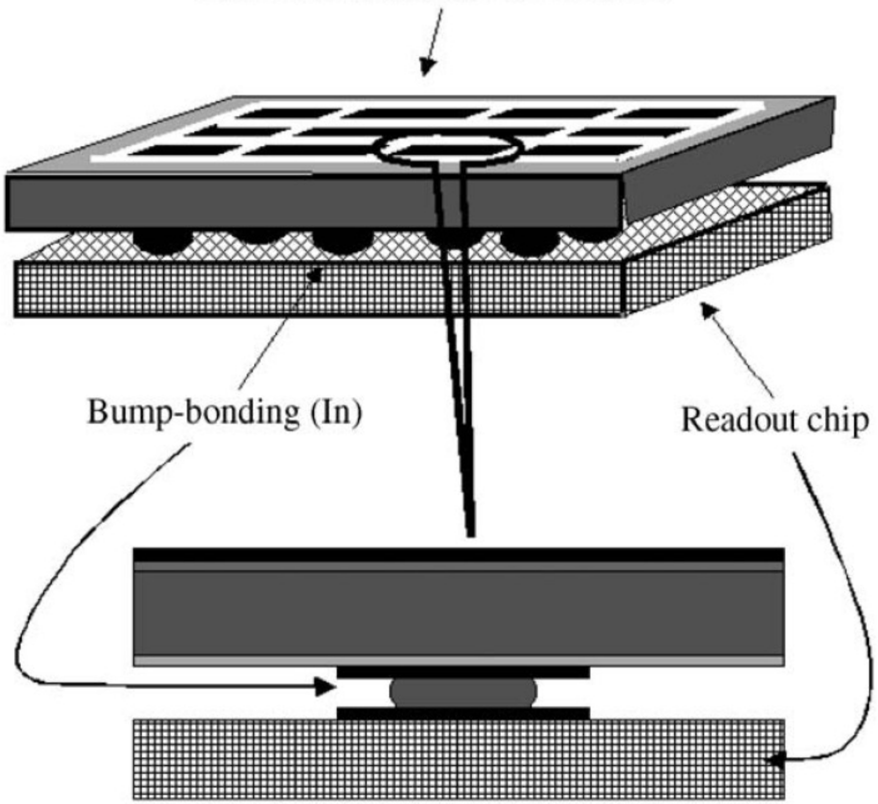
Semiconductor Detector Configuration (Conventional)

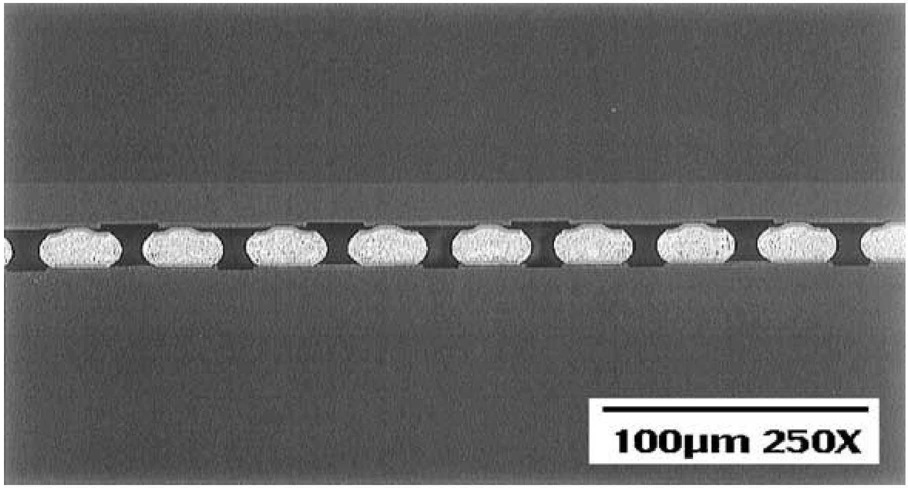
	Spatial Sensitivity	Mostly Used for	Rad-hardness	Processing	Readout
Pixel/Pad	2D Pixel size($\sqrt{A}$): 10 μm to mm's	HEP/NP	Good (small area – small leakage current)	Single-sided	Each pixel (fast, 10's ns)
Single-sided strip	1D Strip pitch: 10 μm to mm's	HE/NP	Modest	Single-sided	Each strip, e's or h's (fast, 10's ns)
Double-sided strip	2D Strip pitch: 40 μm to mm's	HE/NP	Not good (n-side not rad-hard)	Double-sided	Each strip, e's and h's (fast, 10's ns)
CCD (Charge-coupled-device)	2D Pixel size($\sqrt{A}$): >10's μm	X-ray and others (LSST)	Not good (very sensitive to trapping)	Single-sided	Each column (slow, μs's)
Drift **(SDD)** (Si drift detector)	2D Anode size >10's μm	X-ray and others (STAR, ALICE)	Not good (very sensitive to trapping, and to doping change)	Double-sided	Each anode, e's (slow, μs's)
AMPS (JFET) (Active matrix pixel sensor) **DEPFET (PMOS)** (Depleted P-channel FET) Fully depleted	2D Pixel size($\sqrt{A}$): ~100's μm	X-ray and others	Not good (very sensitive to trapping, and to doping change)	Double-sided	Each column (slow, μs's-ms)
MAPS (CMOS) (Monolithic active pixel sensor)	2D Pixel size($\sqrt{A}$): ~10 μm	X-ray and others HEP/NP (STAR)	Modest? (very low resistivity EPI Si)	EPI Si (20-50μm) SOI (fully depleted)	Each column (slow, μs's-ms)

Semiconductor Detector Configuration (new)

	Spatial Sensitivity	Mostly Used for	Rad-hardness	Processing	Readout
2D stripixel	2D Strip pitch: 10 μm to 100's μm s	HE/NP (PHENIX VTX)	Modest	Single-sided	Each strip (fast, 10's ns) (charge sharing)
3D stripixel	2D Strip pitch: 10 μm to 100's μm s D	HE/NP	Good	3D processing Single-sided or double-sided	Each strip, e's and h's (fast, <10 ns)
3D trench (pixel, strip, and stripixel), BNL, patent pending	2D Strip pitch: 100's μm to mm's	HE/NP X-ray	Very good	3D processing Single-sided or double-sided	Each pixel/strip, e's and/or h's (fast, <10 ns)

Pixel detector and bump-bonding technology (Used extensively, CERN, RHIC, etc.)

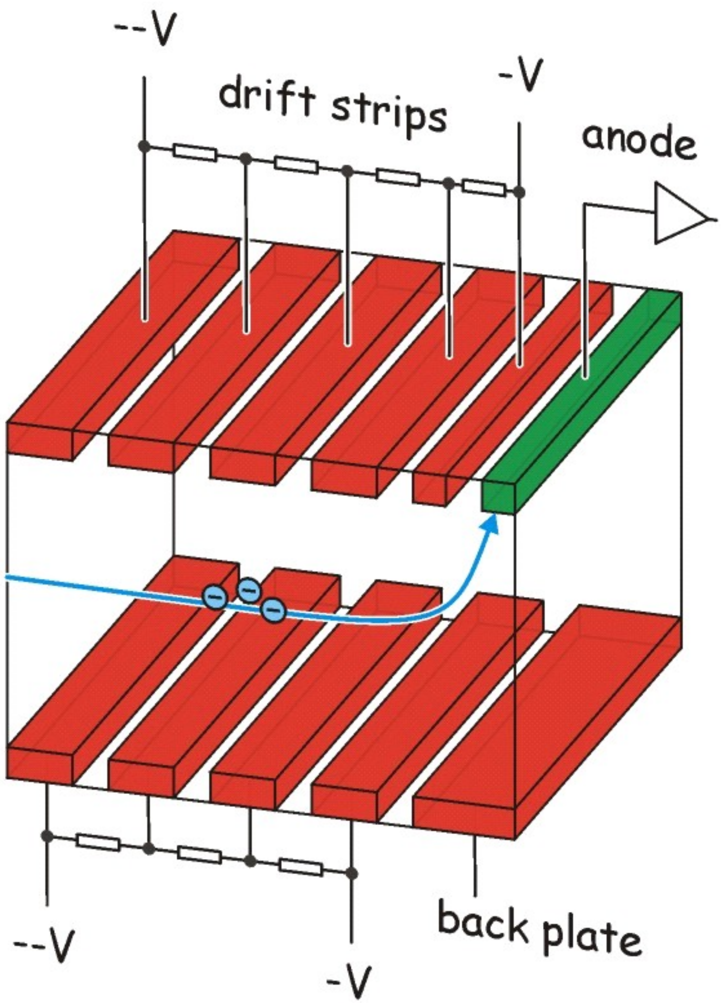


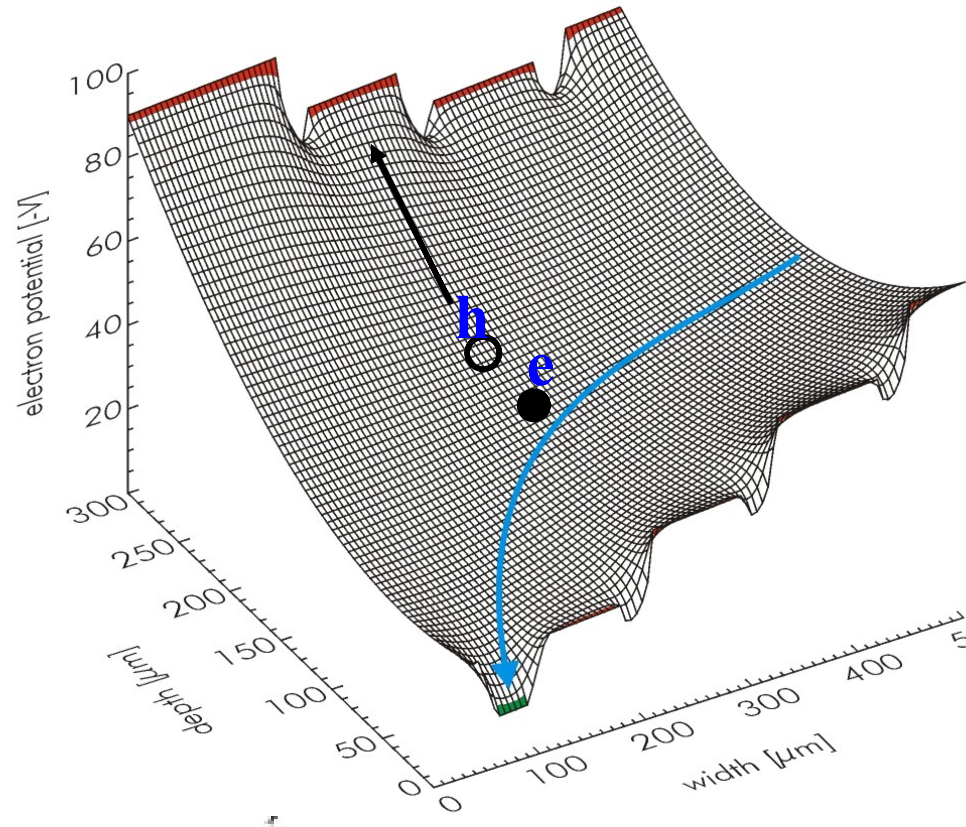


Solder bumps on a fluxless MCNC detector

S. Cihangir, S. Kwan
NIM A 476 (2002) 670–675

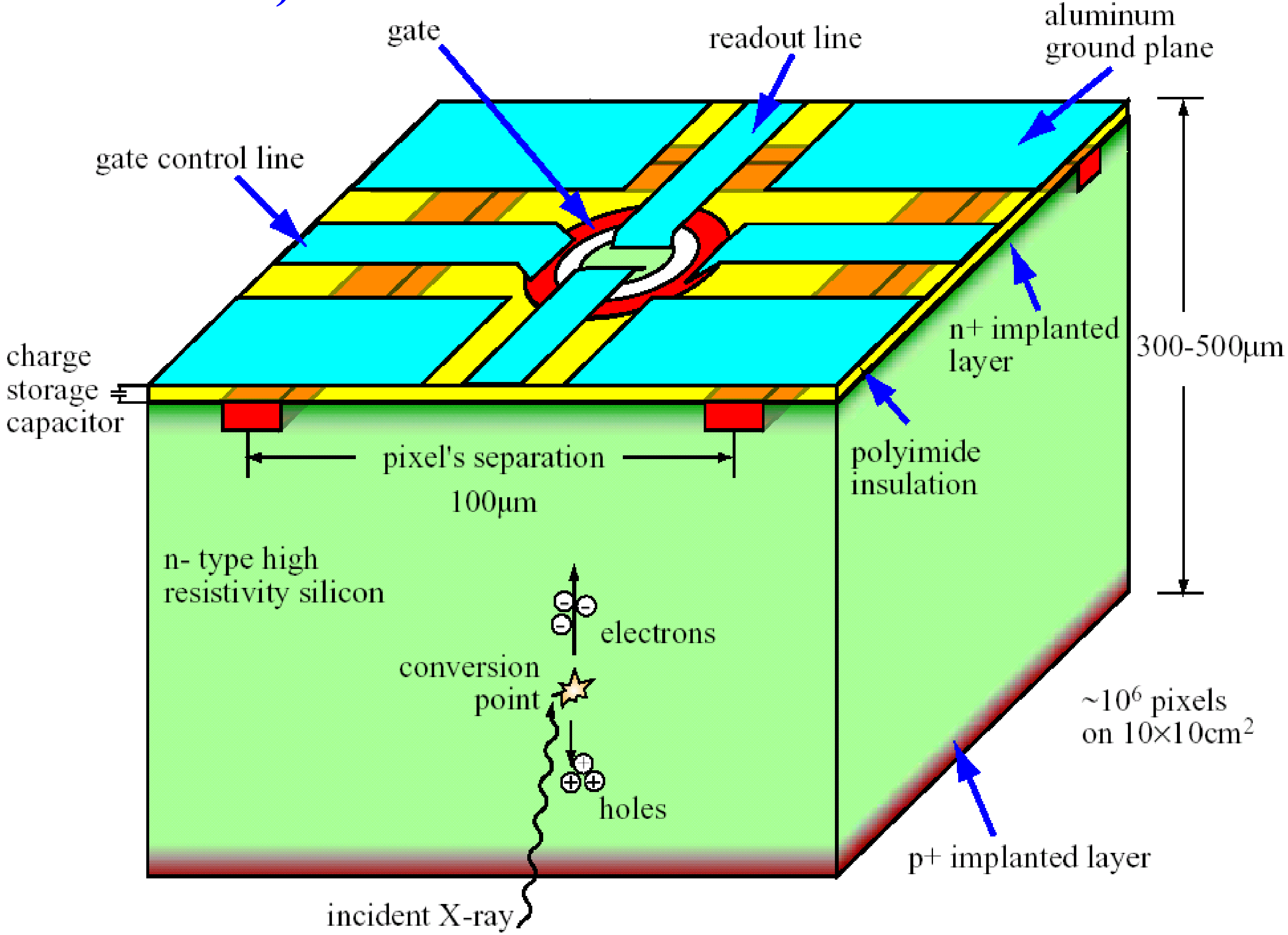
Si Drift Detector (SDD) (STAR, ALICE, X-ray, etc.)





E. Gatti and P. Rehak, "Semiconductor Drift Chamber" – An application of a novel Charge Transport Scheme", Nucl. Instr. and Meth., A 255, pp. 608-614, 1984.

X-ray Active Matrix Pixel Sensor (XAMPS, BNL) (LUSI in SLAC)



Monolithic Active Pixel Sensor (MAPS)-CMOS (STAR)

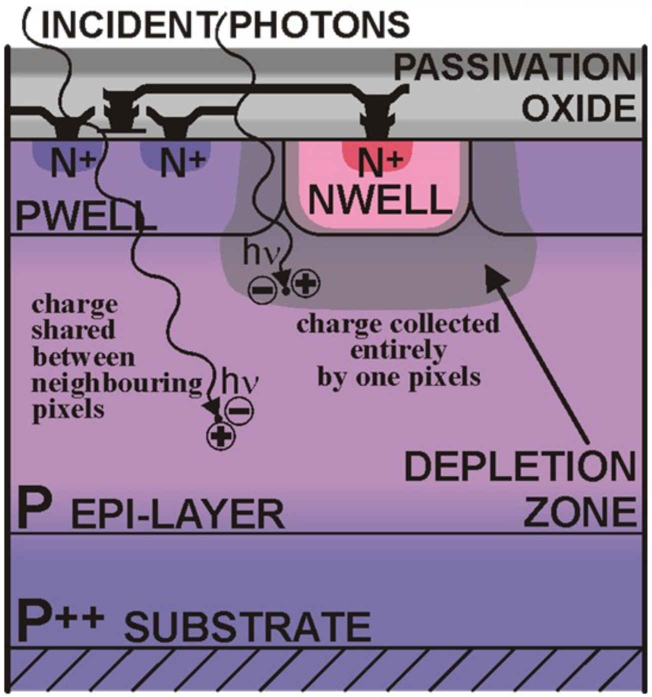
APS Argonne Nat. Lab., December 8-9 2005

Grzegorz DEPTUCH

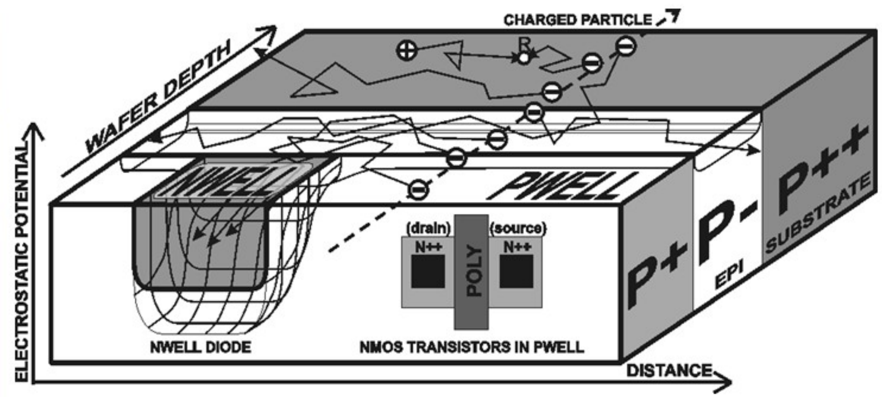
CMOS IMAGE SENSORS IN HEP - MAPS

Operation principle of photodiode MAPS

Monolithic Active Pixel Sensors (MAPS)



structure proposed for visible light
allowing 100% detection efficiency (tracking!)



operation:

- signal generated in epitaxial layer (low doping) $Q \approx 80 e^- h^+ / \mu m \Rightarrow \sim 1000 e^-$,
- charge collection through thermal diffusion,
- signal sensed as voltage drop on N-WELL anodes,
- reflection bondaries at P-WELL and P-SUB.

ADVANTAGES:

decoupled charge sensing and signal transfer (improved radiation tolerance, random access, etc.), small pitch (high tracking precision), low amount of material, fast readout, moderate price, SoC, etc.

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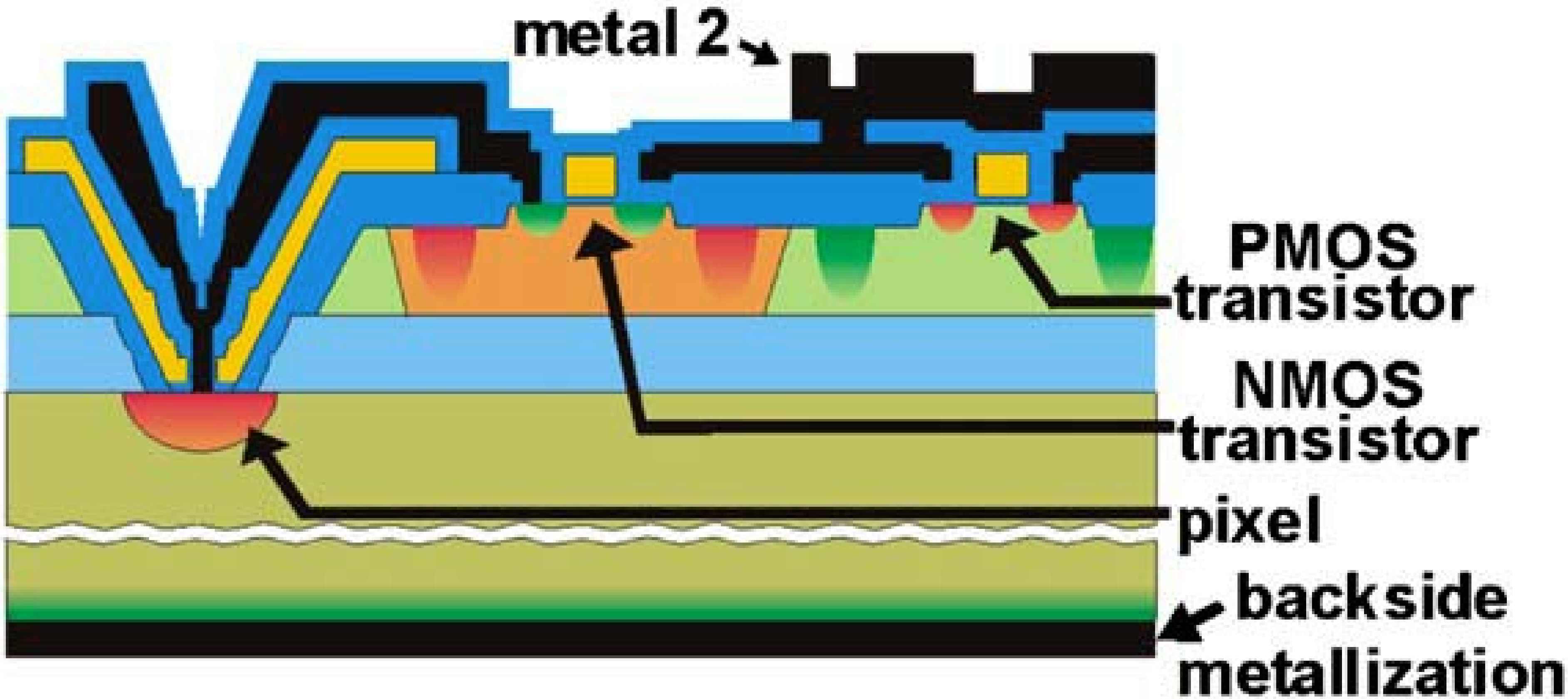
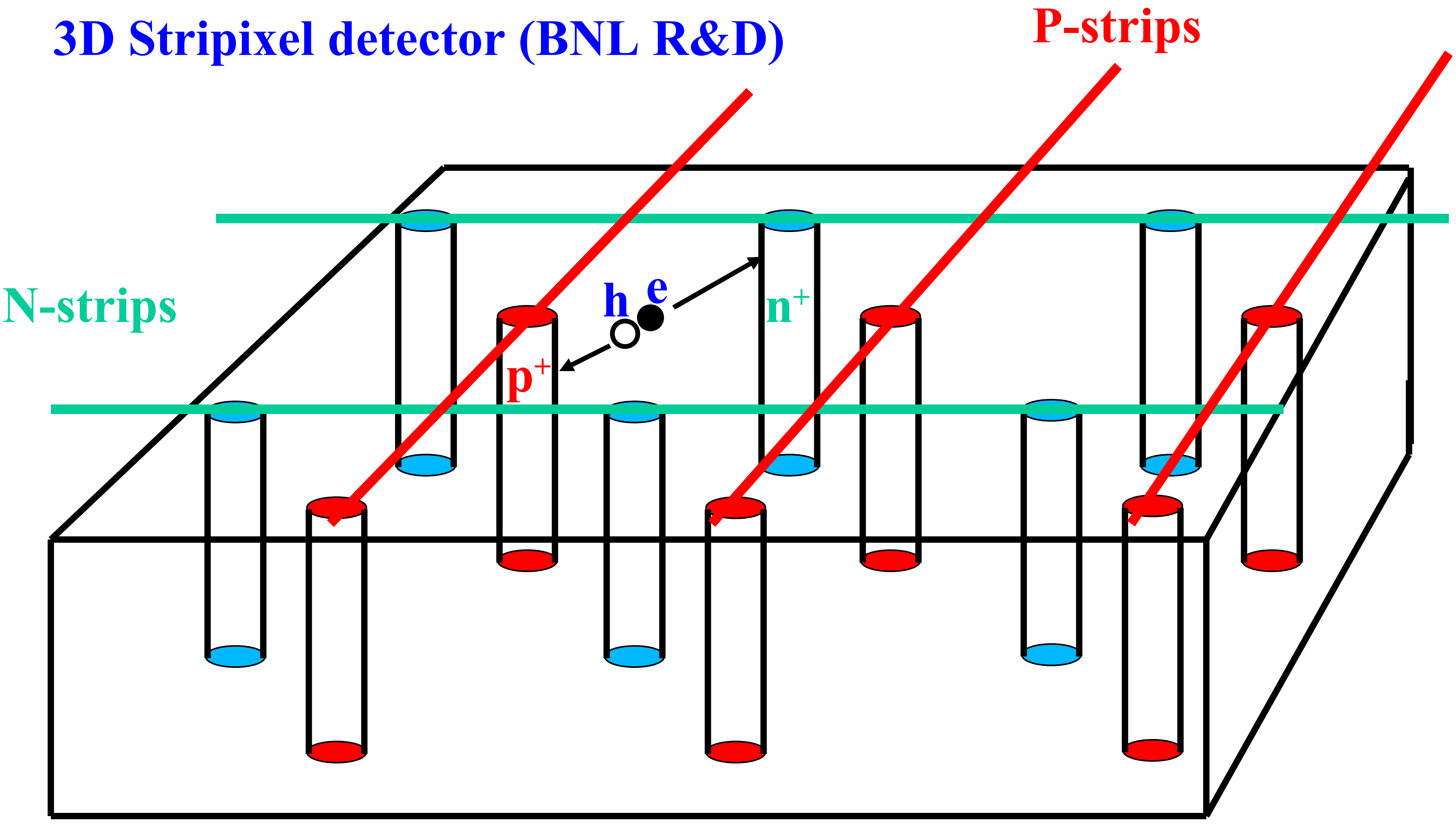
MAPS-SOI (R&D)

J. Marczewski et al., NIM A 549 (2005) 112–116



3D Stripixel detector (BNL R&D)



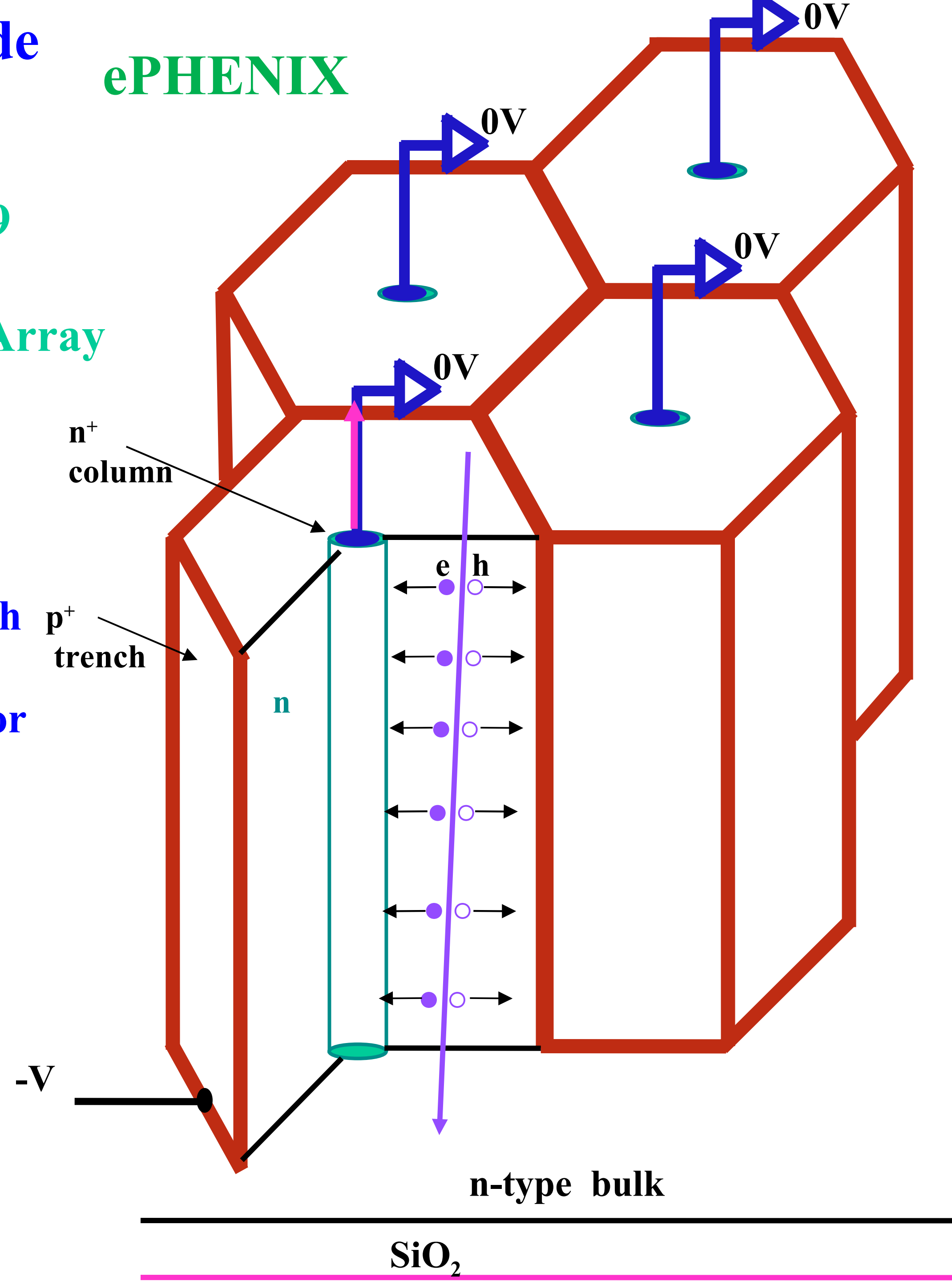
No charge sharing

ePHENIX

- **BNL's 3D-Trench Electrode Detector (R&D)**
  - **New 3D-Trench electrode configuration (Z. Li, 10/2009 BNL)**

or Independent Coaxial Detector Array (ICDA)

ePHENIX



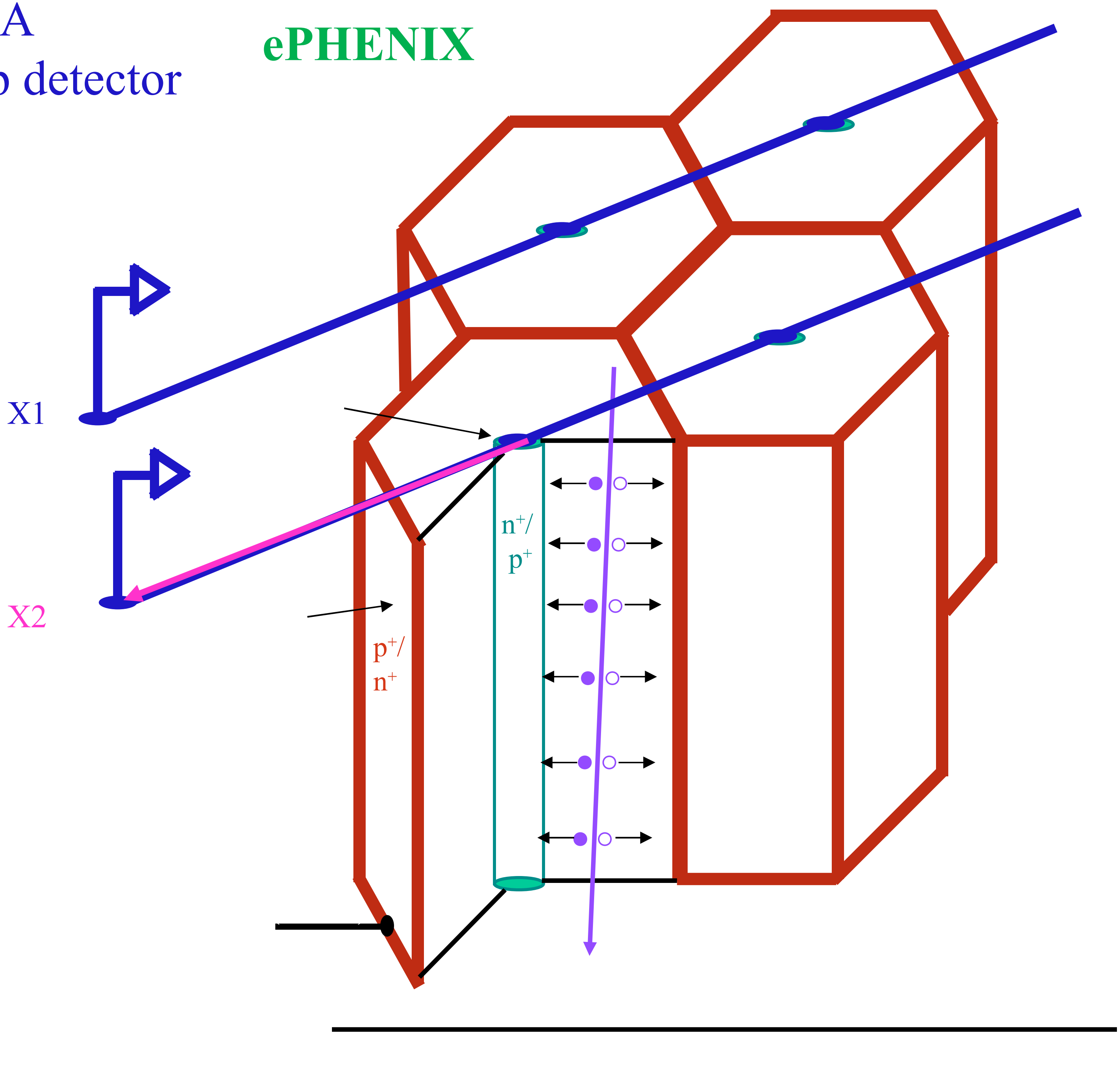
- **Mask set has been design and made**
- **Processing of the first prototype batch will start in 10/2010 at CNM**
- **First prototype batch will be ready for testing in May 2011.**

BNL new 3D-Trench Electrode detector

CT filed on 10/15/2010

CT/US2010/52887)

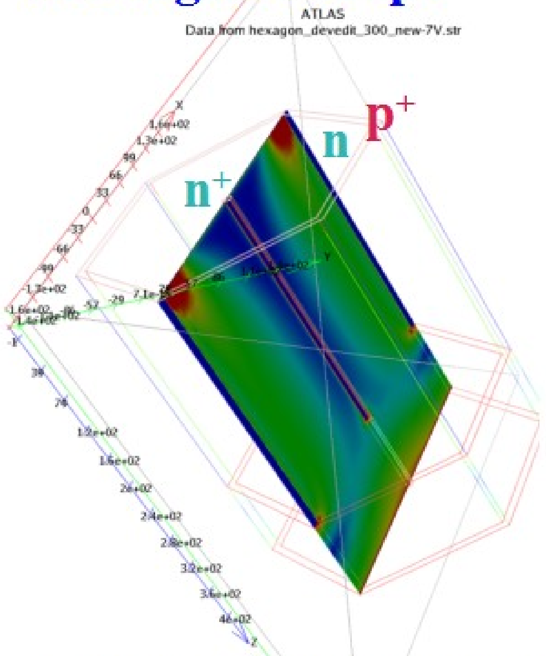
ICDA
Strip detector



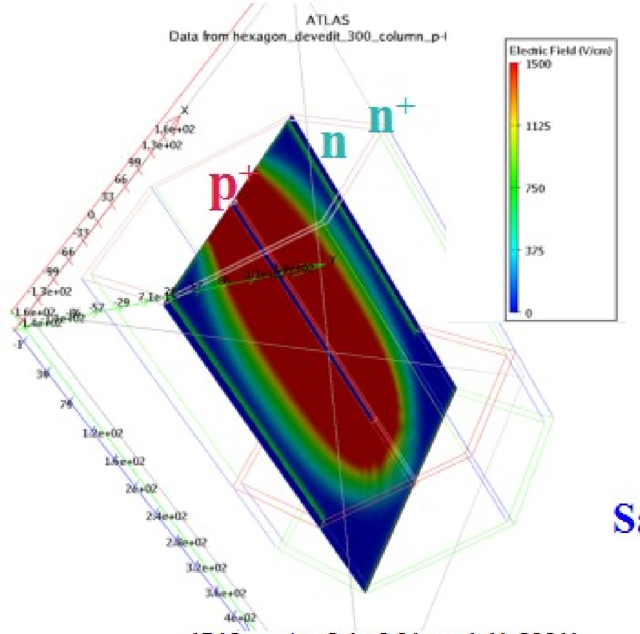
3D simulations of electric field

ePHENIX

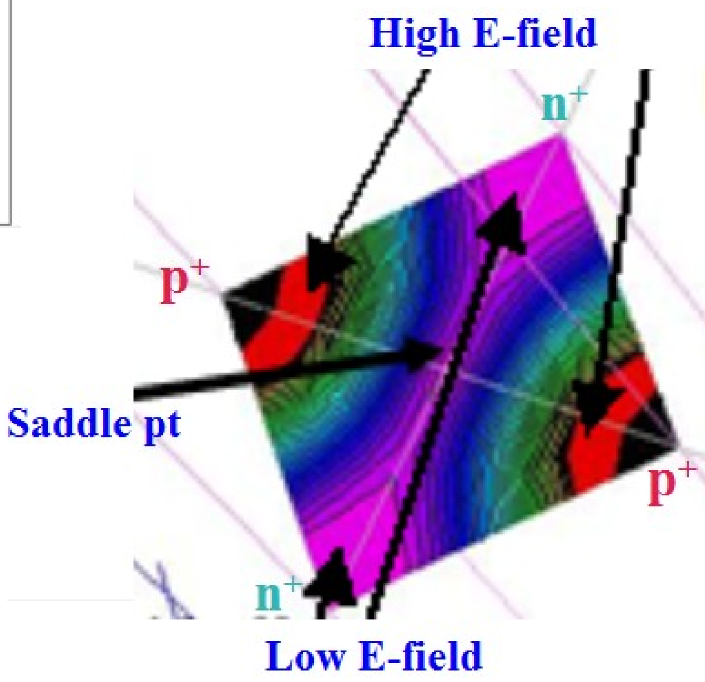
Hexangular shape

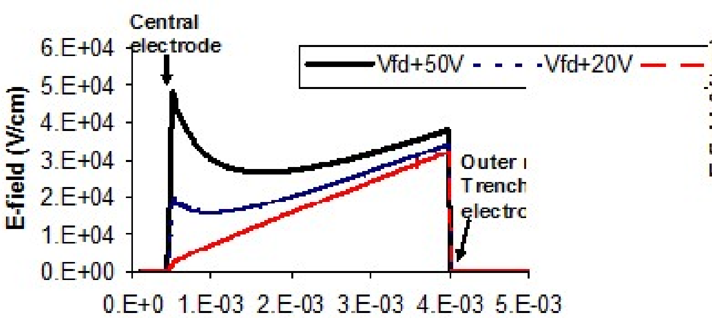


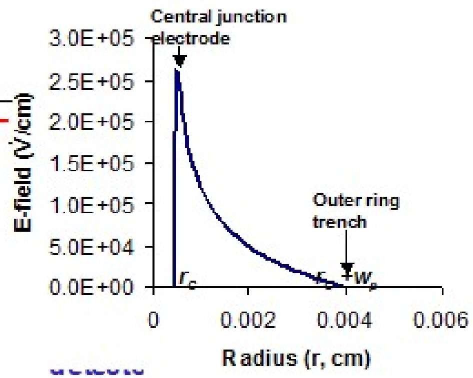
1E16 neq/cm2, b=0.01 cm-1, Vfd=59 V
3D-Trench-ORJ, R = 40 um



1E16 neq/cm2, b=0.01 cm-1, V=206 V







BNL 3D-Trench (Trench Junction)	BNL 3D-Trench (Column Junction)	Early 3D
Full depletion voltage (150 µm electrode spacing):		
8 V, very uniform	52 V, uniform	>52 , very non-uniform

- # Detector Processing Facilities -1

University and National Labs

	Main Detector Technology	Main Material	Wafer size	Particle Physics related
BNL USA	Pixel, Strip/Stripixel SDD, AMPS 3D (Development, simulation, and design)	Si	4”, 6”	US ATLAS CERN RD39 CERN RD50 RHIC (X-ray det for photons)
CNM Spain	Pixel, Strip, 3D	Si	4”	ATLAS CERN RD50
HIP Finland	Pixel Strip	Si	4”	CMS CERN RD39 CERN RD50
LBL USA	Fully-depleted CCD, Strip	Si, Ge	4”	X-ray Astrophysics
MPI Halbleiterlabor Germany	Pixel, Strip, SDD AMPS, DEPFET	Si	4”, 6”	X-ray Astrophysics

- # Detector Processing Facilities -- 2

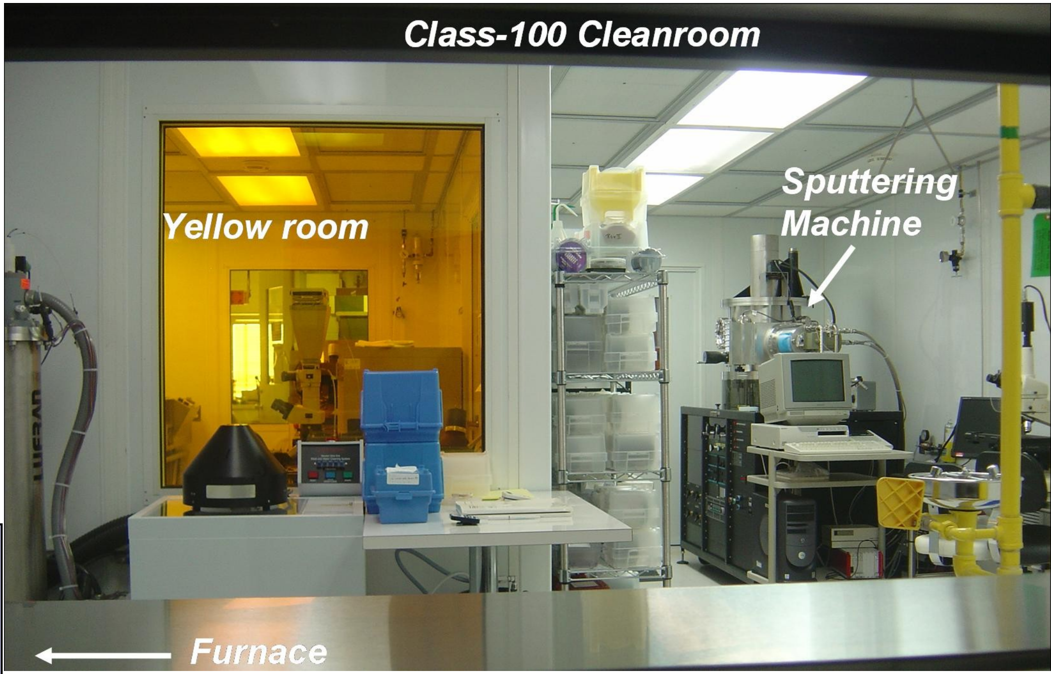
Commercial

	Main Detector Technology	Main Material	Wafer size	Particle Physics related
CiS-MSP Germany	Pixel, Strip	Si	4”	CERN RD50
FBK-IRST (Trento) Italy	Pixel, Strip, 3D	Si	4”, 6”	CERN RD50
Hamamatsu Japan	Pixel, Strip, Stripixel (No double-sided)	Si	4”, 6”	LHC/sLHC
KETEK Germany	SDD AMPS	Si	4”, 6”	X-ray
Micron Semiconductors UK	Pixel Strip	Si	4”, 6”	CMS CERN RD39 CERN RD50
SINTEF Norway	Pixel, Strip, 3D	Si	4”, 6”	ATLAS

BNL Si Detector R&D Program

- Scientific and engineering resources in the Instrumentation Div.
- Silicon detector processing facility

- Detector fabrication capability:
  - Process and device simulation
  - Detector and mask design
  - Processing steps (oxidation, photolithography, metallization)
  - Testing and characterization



Detector R&D

Silicon Drift Detectors
Stripixels, strip, and pixel
Radiation resistant Silicon
XAMPS
For NP,HEP, Photon science

- **Fabrication**

550 ft^2 Class-100 cleanroom

Summary

- Si detectors are still the detector of choice for NE, HEP, and photon sciences

- Many detector configurations and technologies are readily available for application needs (sPHENIX)

- New 3D technology and detectors are now developed, and can be used for future applications (ePHENIX)

- BNL is at the forefront of the prototype and novel detector development and fabrications